INVESTIGATION OF HOT CARRIER RELAXATION WITH PICOSECOND LASER PULSES

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Résumé - La disponibilité récente de lasers sous-picoseconde a augmenté l'utilisation de techniques optiques pour l'étude de la relaxation de porteurs chauds dans les semiconducteurs.
Dans cet article, nous présenterons d'abord des concepts théoriques de base associés à l'étude à la picoseconde de la relaxation des porteurs.
Nous exposerons ensuite des résultats expérimentaux sur la relaxation des porteurs chauds dans l'AsGa à la suite d'une excitation par un laser sous-picoseconde. Les temps de relaxation observés seront comparés à la théorie et on mettra en évidence l'écrantage de l'interaction electron-phonon.
Enfin deux expériences récentes combinant des techniques de transport et d'optique à la picoseconde seront discutées pour illustrer leur utilisation et les possibilités des impulsions laser à la picoseconde dans l'étude des effets des porteurs chauds dans les semiconducteurs.

Abstract - Recent availability of subpicosecond lasers has enhanced the usefulness of optical techniques in the investigation of hot carrier relaxation in semiconductors by allowing us to directly probe the carrier distribution function on picosecond timescales. In this review, we will first discuss some basic theoretical concepts related to picosecond investigation of carrier relaxation. We will then review recent experimental results on hot carrier relaxation in GaAs following excitation by a subpicosecond laser. Observed relaxation rates will be compared with theory and evidence for the screening of electron-phonon interaction will be presented. Finally two recent experiments combining transport and picosecond optical techniques will be discussed to further illustrate the utility and possibilities of picosecond laser pulses in the investigation of hot carrier effects in semiconductors.

1. Introduction. - Physics of hot carriers deals with the many complex and interesting problems relating to energy and momentum exchange between electrons and holes, between carriers and phonons, and between carriers and impurities or imperfections. An understanding of these interactions is important not only from a fundamental viewpoint but also for modelling the performance of semiconductor devices, particularly those based on the transport of charge carriers at low and high electric fields. Early impetus for the work on hot electron physics was provided by devices such as Gunn oscillators which depend for their operation on the transferred electron effect. With the present trend towards smaller and faster devices, and the emergence of VLSI technology, the study of nonlinear electronic transport and hot electron physics remains an active area of research.

Classical transport measurements have contributed much to our understanding of various carrier scattering processes and have

also provided quantitative information about the average energy and momentum scattering rates for these processes.[1] Optical measurements complement these transport measurements in many respects. While transport measurements provide a measure of the average carrier response to an applied electric field, optical measurements offer the best means of determining the electron and hole distribution functions (DF) and the microscopic (i.e., not averaged over a DF) scattering rates so important for a theoretical description of the transport processes. Various sensitive and high energy resolution optical techniques such as transmission, reflection, emission and Raman spectroscopies have been used in the past to probe these aspects of the carrier system under various experimental conditions. Some of these techniques have been discussed in recent reviews.[2,3]

Optical techniques have been applied to the hot electron field in another way also. It has been shown that even in the absence of an external electric field, optical techniques can be used to <u>create</u> a hot, nonequilibrium carrier distribution.[4,5] Further, the heating of carriers by photoexcitation can be controlled by controlling such parameters as the excitation intensity (I_x) and/or the excitation photon energy (E_x).[4,5,6] In contrast to the case of electric field induced heating, photoinduced heating is found[4] to generally produce a Maxwellian DF, although non-Maxwellian DF have been produced under extreme conditions.[7] While the mechanism of generating hot carriers by photoexcitation is quite different from heating by an electric field, the same carrier relaxation and scattering processes apply in both cases. Thus the ability to create and probe hot carriers by optical techniques has become a powerful means of studying the processes important in hot electron physics.[8,9]

The recent development[10] of picosecond and subpicosecond lasers have immensely increased the value of these optical techniques by extending the timescale on which meaningful measurements can be made into a range not accessible as yet to purely electrical methods. Since many of the scattering processes important to carrier dynamics occur on this time scale, one has the ability, in principle, to determine directly these scattering rates and even to monitor the time evolution of DF at very short times. In this review we will discuss the recent work applying the picosecond optical techniques to III-V semiconductors of which GaAs is a prototype.[11] Many exciting results have already been obtained. A direct measurement of carrier cooling rate has been made.[12,13,14] The importance of the screening of electron-phonon interaction has been established.[13]

Carrier relaxation in two-dimensional quantum wells[15] and velocity overshoot of electrons in a high electric field[16] have been investigated. Super high-density ($\geq 10^{20}$ cm^{-3}) plasma has been generated[17] by using picosecond pulses and studied by observing the resulting short-pulse semiconductor laser dynamics. These many varied results make it clear that picosecond lasers provide a means of determining many parameters which are important in hot electron physics and whose knowledge is essential in understanding the smaller and faster semiconductor devices of today and tomorrow. In this review, we will first discuss some important theoretical considerations (Sec. II), and then discuss recent experimental work in this field (Sec. III).

II. Theoretical Considerations

II.A Photoinduced Heating of Carriers

        The absorption of photons by a semiconductor generates a nonequilibrium carrier distribution in the conduction and/or valence bands.[18] These nonequilibrium carriers relax extremely rapidly ($\lesssim$ 1psec) to the band extrema by emitting phonons and plasmons, and by interacting with other carriers. Since the typical carrier lifetimes are at least a couple of orders of magnitude larger than these relaxation times, the density of the system of carriers near the band extrema is much larger than the density of the relaxing photoexcited carriers, except at times immediately following the excitation by a subpicosecond laser pulse. Let us first consider the case of CW excitation (defined here as any experiment with time resolution larger than ~ 1 nsec). The photoexcited electrons generated with an excess energy ΔE_e (Fig. 1) exchange a fraction f of this energy with the carriers at the bottom of the band through carrier-carrier scattering; the remaining energy is given to the lattice by the emission of (mostly) optical phonons. The fraction f depends on many para-
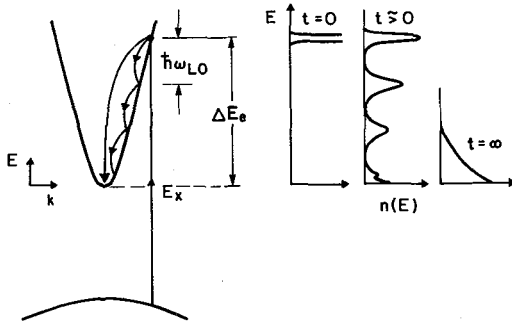

Fig. 1 Schematic diagram showing (left) relaxation processes following interband absorption and (right) carrier DF at three time delays

meters including ΔE_e, the carrier density, and the intercarrier and the carrier-phonon energy exchange rates. The carrier system loses this excess energy to the lattice also by emission of phonons. If the rate of energy input to the carrier system is sufficiently large, the average energy of the carriers becomes measurably larger than $\frac{3}{2} kT_L$ where T_L is the lattice temperature. The relative values of various energy exchange rates and the carrier lifetimes determine whether the carriers can be described by an equilibrium (Maxwell-Boltzmann or Fermi-Dirne) DF with a carrier temperature $T_C > T_L$ or a nonequilibrium distribution for which a temperature cannot be defined.[4]

      Photoexcitation by picosecond lasers involves somewhat different considerations. One asks the question: how does a mono-energetic carrier distribution created by an ultrashort light pulse evolve with time. Optical pulses shorter than 0.1 psec have recently become available.[19] Since this is comparable to the phonon emis-sion time by an electron with ~0.1 eV energy in GaAs, an electron cascading down the conduction band by emitting LO phonons (Fig. 1) may take several pulse widths to reach an energy less than $\hbar\omega_{LO}$ (the phonon energy). During this time, an appropriate description of the carrier-carrier interactions is difficult to define. However, the cascading electrons can be expected to lose energy by collective ex-citations (plasmons) of the photoexcited carrier system and direct carrier-carrier collisions. Both these processes depend on electron densities. Therefore, depending on the photoexited carrier densities and other material and photoexcitation parameters, the DF may evolve in a complicated manner for times of the order of 1 psec, as illus-trated schematically in Fig. 1 ($t \gtrsim 0$). At longer times, a steady state similar to that obtained for CW excitation emerges and the DF becomes a Maxwellian for sufficiently high carrier densities as il-lustrated in Fig. 1 ($t = \infty$).

      While these concepts are simple in principle, several com-plications must be considered for a realistic semiconductor. In case of GaAs, the presence of light and heavy valence bands and their warping creates complications. The presence of screening of various interactions at high carrier densities, nonlinear effects (e.g., large disturbance in the phonon population generated by cas-cading electrons) and nonuniform carrier densities must be con-sidered. Detailed theoretical calculations taking account of these effects would be extremely useful both for the CW and subpicosecond excitations.

II.B High Density Plasma in a Semiconductor

Picosecond lasers provide a unique technique of exciting a high-density plasma without damaging the semiconductor; densities in excess of 10^{20} electron-hole pairs/cm^3 can easily be achieved.[17] The presence of a dense plasma modifies the properties of a semiconductor, and an understanding of these modifications is essential for the interpretation of experiments. We therefore present a brief review of our present understanding in this field.

At low temperatures and in the absence of carriers, the optical absorption spectrum of intrinsic GaAs consists of one (or more) sharp exciton absorption lines at energies slightly below the bandgap energy E_g, followed by a slowly rising continuum above E_g (Fig. 2a). The sharp lines are due to hydrogen-like bound states of
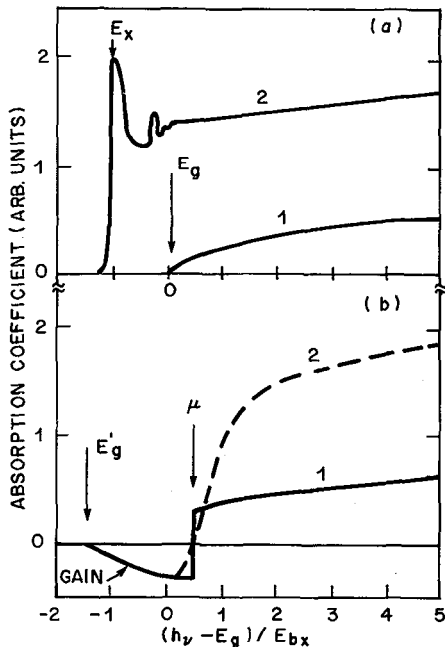

Fig. 2 Schematic diagram of the low temperature absorption coefficient of a direct gap semiconductor like GaAs. (a) without and (b) with photoexcited carriers. Curves 2 include excitonic effects which are neglected in curves 1.

excitons while the continuum is due to interband absorption considerably enhanced by excitonic contributions. With the excitation of a high density plasma in GaAs, the discrete exciton states are screened and the enhancement of the absorption coefficient α above E_g is reduced for $(h\nu - E_g)$ less than and comparable to $\hbar\omega_p$ where ω_p is the plasma frequency. However, the enhancement for $(h\nu - E_g) \gg \hbar\omega_p$ is not affected.[20] In addition, the exchange and correlation effects in the electron-hole plasma result in a renormalization (reduction) of the bandgap.[21,22] Similar phenomena are responsible

for the creation of electron-hole droplets in materials such as Ge
and Si, and electron-hole liquids in materials such as GaP[23] and
CdS.[24] Experimentally important parameters, the renormalized band-
gap energy E_g' and the chemical potential μ (= E_g' + the sum of the
electron and hole quasi-Fermi energies), can be deduced from the
theoretical calculation of exchange and correlation energies. Re-
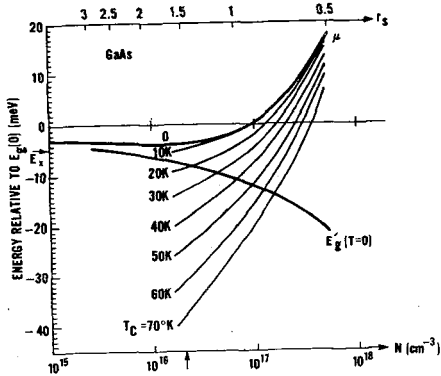sults of such a calculation[20] for GaAs are shown in Fig. 3. One

Fig. 3 Calculation of the re-
normalized bandgap energy (E_g')
and the chemical potential (μ)
in GaAs as a function of density
at various temperatures (from
Shah et al., Ref. 20).

expects optical gain for E_g' < $h\nu$ < μ and optical absorption for
$h\nu$ > μ. At T_L = 0, the transition from gain to absorption is sharp;
at finite T, the carriers also occupy states above μ and affect α for
$h\nu$ > μ. These screening, renormalization and band-filling effects
lead to changes in the absorption spectrum as illustrated in
Fig. 2b. Analysis of a measured absorption spectra at various de-
lays including these effects can, in principle, allow one to deter-
mine the DF as a function of time. Similar information can also be
obtained from band-to-band luminescence experiments providing these
plasma effects are accounted for properly.

        The simplified picture described above has to be modified
in several respects in a realistic case. The difficulties associ-
ated with deducing a DF from the measured absorption spectrum have
been discussed earlier.[2,3] The theories of exchange and corre-
lation energy for high density plasma in semiconductors have only
been developed for T = 0 and may have to be modified drastically at
high carrier temperatures or for the non-Maxwellian DF expected in
picosecond measurements. Auger recombination, plasma expansion,
etc., also need to be considered. A great deal more theoretical
work is required to properly account for these effects.

II.C Cooling of a Hot Carrier Distribution

        We are interested in calculating the average energy loss
rate per electron-hole pair $\langle\frac{dE}{dt}\rangle$ = P_C for a Maxwellian DF of

electrons and holes which are at a temperature T_c greater than the lattice temperature T_L. For electrons, P_c is dominated by polar optical phonons at high T_c and acoustic phonons $T_c < 30$ k. Holes exhibit similar behaviour, however, the hole-acoustic phonon coupling is much larger because of the heavy mass of holes in GaAs. For this reason P_c is completely dominated by holes for $T_c < 40$ k. At higher temperatures where interactions with optical phonons dominate, both polar and nonpolar interactions are important for the holes because of their p-like wave functions.[25] Goebel and Hildebrand[26] have considered these factors in detail. Using $m_e = 0.07\ m_o$, $m_h = 0.62\ m$, and other values of parameters same as by Goebel and Hildebrand, we obtain the curve shown in Fig. 4 for P_c as a function of T_c. The actual values will be somewhat ($\sim 50\%$) higher when nonpolar scattering of holes is included. The rate $\langle\frac{dT}{dt}\rangle$ is ($P_c/3k$), and is also shown in Fig. 4. One can now calculate $T_c(t)$ simply by
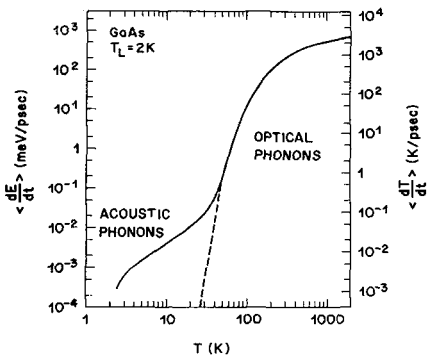

Fig. 4 Calculated average energy loss rate per electron-hole pair for a Maxwellian plasma at temperature T in GaAs (after Goebel and Hildebrand, Ref. 26).

integrating this curve for a given initial temperature $T_o = T_c(o)$. Some examples are shown in Fig. 5. We have introduced an adjustable carrier-phonon coupling parameter C into the calculations. C = 1 corresponds to the curve shown in Fig. 4; thus effective $P_c = C \times$ (P_c shown in Fig. 4) can be defined to take account of the change in carrier-phonon interaction due to screening and other effects. We note that the rate of cooling slows down with time and becomes extremely slow when $T_c < 40$ k where acoustic phonons dominate. For a typical carrier lifetime of 10^{-9} sec, the carriers are likely to recombine before reaching a lattice temperature $T_L = 2$ k.

III. Experimental Results

Several techniques for generating picosecond and subpicosecond optical pulses have been developed in recent years.[10] The use of these picosecond sources in studying hot carrier relaxation
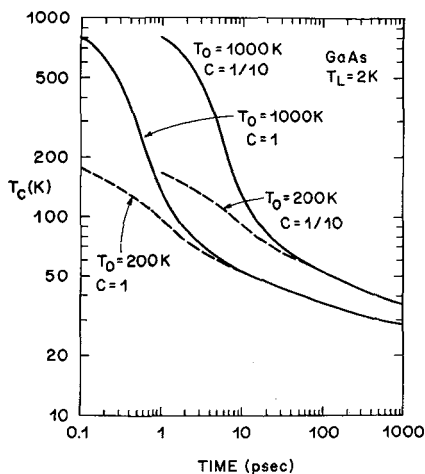
Fig. 5 Calculated variation of the carrier temperature T_C as a function of time delay for the initial temperature T_0 = 1000K, and T_0 = 200 K, and C = 1 and 1/10.

in semiconductors can be best illustrated by discussing some recent experiments performed by using these techniques. We first discuss a set of experiments performed on GaAs at low temperatures by Shank et al[12] and Leheny et al.[13] A passively mode-locked dye laser (pulsewidth 0.5 psec) was cavity dumped and amplified in a three-stage amplifier pumped by a frequency doubled YAG laser.[27] The amplified beam was split into two beams; one beam was focused on a cell containing ethanol to generate a Raman shifted beam at 1.65 ev which photoexcited the crystal of GaAs. Changes in the absorption spectrum of the photoexcited GaAs were monitored with broadband sub-picosecond continuum generated by focusing the second amplified beam into a cell containing water.[27] A controlled time delay between the pump and probe pulses was introduced by varying the optical path length of the probe beam. For a fixed delay, the entire absorption spectrum in the region of interest could be recorded for every pulse and averaged over a large number of pulses by using an optical multi-channel analyzer (OMA). Alternatively, the time evolution of absorption at a given photon energy could be measured by varying the optical delay with a stepper motor while recording the signal from a single channel of OMA into a signal averager.

The transmission spectrum of GaAs obtained with such a picosecond continuum, in the absence of pump pulses (τ < 0), is shown in Fig. 6a. This represents the unperturbed transmission spectrum obtained when no photoexcited carriers are present. It shows high transmission below the bandgap (λ > 8150 Å), a sharp dip at exciton energy and a slowly decreasing transmission at shorter
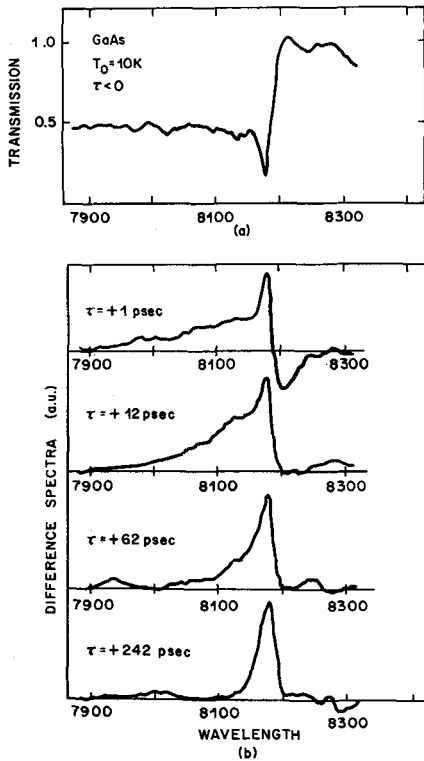
Fig. 6 (a) Transmission spectrum of GaAs obtained with 0.5 psec broadband continuum pulses without any photoexcitation. (b) Difference spectra at various time delays following excitation by a 0.5 psec pump pulse (from Leheny et al., Ref. 13)

_wavelengths (compare with curve 2 of Fig. 2a). In Fig. 6b we present the difference spectra at various time delays (τ = 1 psec to 242 psec) obtained by subtracting the unperturbed spectrum of Fig. 6a from the measured spectrum at a given delay τ; (i.e., a positive signal implies an increase in transmission). The important feature of the data are as follows: For $h\nu < E_g$, there is a decrease in transmission at 1 psec which was attributed to the shift in the absorption edge due to the renormalization of the bandgap (Section II B). This decrease in transmission does not persist beyond $\approx$ 12 psec because the photo-excited carriers fill the states between the renormalized bandgap (E_g') and the unperturbed bandgap E_g. For sufficiently high excitation density, one observes gain between E_g' and the chemical potential μ (see Fig. 2b). The second feature of the data is a sharp increase in transmission at E_x, attributed to the screening of exciton bound states. A remarkable feature of the data is that the screening and renormalization are effective in < 1 psec while the majority of carriers occupy states high in the band and persist for at least

242 psec. The third important feature of the data is the increase in
transmission at shorter wavelengths ($h\nu > E_g$) which was attributed to
changes in the Fermi occupation factors or the distribution function
DF. Each of these features represent the observation of important
changes in the characteristics of GaAs on a time scale never before
accessible, but we will restrict our discussion here to the analysis
of this last feature which is the one of most interest for determining
hot carrier relaxation rates in GaAs.

To obtain more quantitative information about carrier
relaxation rates, the measured transmission spectra at various delays
were fitted using the methods previously applied to the analysis of
the steady state experiment.[20] The carrier density (n) and temp-
erature T_c were treated as adjustable parameters. The fit for the
spectra measured at $\tau = 10$ psec for three different excitation inten-
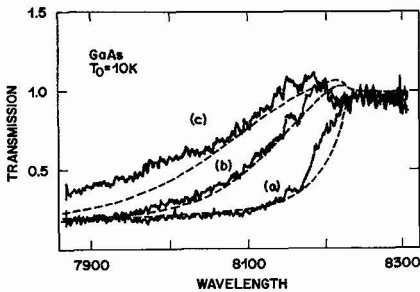sities I_x are shown in Fig. 7. At the highest I_x (curve (c)), there

Fig. 7 Transmission spectrum of
GaAs at 10 psec following photo-
excitation at three pump intensi-
ties I_0, $4I_0$ and $15I_0$ with $I_0 =$
2×10^7 W/cm^2. Dashed curves are
theoretical fits as described in the
text for (a) n = 7 x 10^{16} cm^{-3},
T_C = 50 K (b)n = 3 x 10^{17} cm^{-3} and
T_C = 90 K and (c) n = 1 x 10^{18} cm^{-3}
and T_C = 140 K (from Leheny et al.,
Ref. 13).

is considerably larger population at shorter wavelengths than pre-
dicted by Maxwelliam DF. Similar nonequilibrium distributions have
also been inferred from CW photoluminescence experiments.[7] At
lower I_x, Maxwellian DF is a good approximation as shown in curves (a)
and (b). Curves for $I_x = I_o$ were analyzed for various τ and the car-
rier temperatures obtained from such fits are plotted as a function
of time delay τ in Fig. 8. The points corresponding to curves (b)
and (c) in Fig. 7 are also shown.

There are two major points of interest in Fig. 8. First of
all, one can ask the question if $T_c(t)$ can be fit to the theory of
energy loss rates (Section II C). Assuming that all the excess
energy ($\approx$ 120 meV) of photoexcited carriers is effective in heating
the carriers (i.e., the initial temperature T_o = 465K) Leheny et
al.[13] obtained a reasonably good fit to the data as shown by the
lower solid curve in Fig. 8. The energy loss rate used for this fit
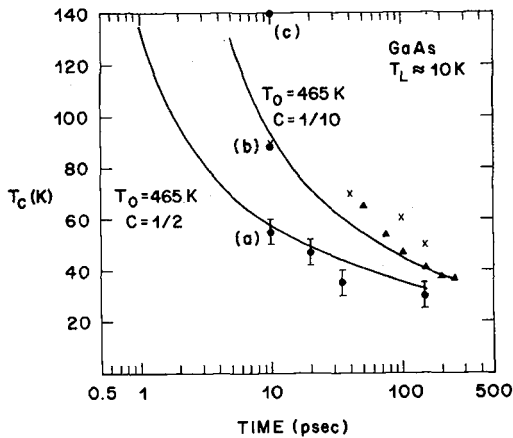was approximately 1/2 the values shown in Fig. 4; hence we have

Fig. 8 The measured variation of T_C with time delay; circles (Leheny et al., Ref. 13) triangles (von der Linde and Lambrich, Ref. 14) crosses (Tanaka et al., Ref. 31). The points (a), (b) and (c) correspond to the three curves in Fig. 7. Theoretical curves for T_0 = 465K and C = 1/2 and 1/10 are also shown.

labelled the curve T_0 = 465K, C = 1/2. The effect of reducing T_0 is negligible for the time delays > 10 psec (see Fig. 5). One can therefore conclude that the observed energy relaxation rate is somewhat slower than the values calculated in Section II (Fig. 4). The second major point of interest is that the measured temperature at a fixed time delay increases with increasing I_x, showing that the energy loss rate to the lattice decreases at higher excitation densities. An explanation of this reduction in terms of the screening of electron-phonon interaction was suggested by Leheny et al.[13] Assuming a further reduction of C by a factor of five (i.e., C = 1/10), the calculated curve passes close to the measured point (b). Effects of the screening of the electron-phonon interaction were calculated by Ehrenreich[28] in 1959. The experiments described above provide the first measurement of this effect and demonstrate the importance of picosecond lasers in investigating carrier relaxation in semiconductors.

Results similar to those described above were also obtained by von der Linde and Lambrich,[14] who used two photon absorption of 25 psec pulses from a YAG laser to excite GaAs and a delayed, frequency-tunable parametric oscillator to measure the resulting changes in the transmission. Their results for T_C vs time delay are also represented in Fig. 8. We see that their results fit the C = 10 curve better, suggesting that screening effects were important in these measurements. von der Linde et al.[29] have also investigated the lifetime of photoexcited nonequilibrium phonons by using similar techniques.

Luminescence measurements have played an important role in investigating hot carrier relaxation in CW experiments.[4,5] With the development of streak cameras, optical shutters and up conversion techniques,[30] luminescence studies on picosecond timescales are possible. Some luminescence studies have already been reported in GaAs.[31,32,33] Tanaka et al.[31] have measured the time resolved luminescence spectra of GaAs excited by 20 psec pulses from a fre-quency-doubled YAG laser by using a CS_2 optical Kerr shutter. Their spectra at various time delays are shown in Fig. 9. These spectra
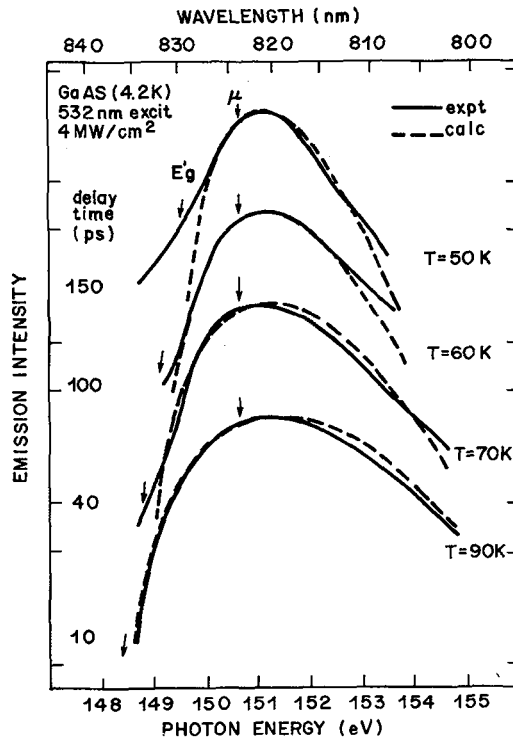

Fig. 9 Luminescence spectra of photoexcited GaAs at various time delays (from Tanaka et al., Ref. 31).

were fitted by using an analysis very similar to that described above for absorption measurements. These fits, along with the values of E_g', μ and T_c obtained from the fits are also shown in Fig. 9. We have plotted these T_c in Fig. 8; we note that these points also fit the $C = 1/10$ curve reasonably well, suggesting that screening effects were important in these measurements. It is also interesting to note that E_g' approaches E_g with increasing time delay; thus the temperature and

density of photoexcited plasma in GaAs decrease with time. Precisely the same effects were observed on a much longer (~nsec) timescale in photoexcited Si by Shah and Dayem.[34]

Another interesting application of picosecond lasers is to generate and investigate very high density plasma in semiconductors. Damen et al.[17] have recently produced densities in excess of 10^{20} cm^{-3} in a GaAs platelet sandwiched between two dielectric mirrors. Laser action at wavelengths as short as 7700 Å was observed, and the time evolution of this laser action was investigated. Many complex physical phenomena determine the response of semiconductors under such high excitation densities. One phenomenon relevant to the discussion here is the intervalley relaxation between Γ and L or X valleys. The densities excited here are high enough that electrons occupy not only the Γ valley but also the L and possibly X valleys. Understanding the response of the system can provide information about such intervalley transitions.

These picosecond techniques can be applied to investigate hot carrier relaxation processes in other semiconductors. Results on CdSe have been reported.[35] Hot carrier relaxation in GaAs-AlGaAs multiple quantum wells have been investigated recently[15]. It is clear that many interesting experiments will be forthcoming in this field.

In the experiments described above, the picosecond pulses were used to heat the carriers as well as to probe the carrier DF following such photoinduced heating. Picosecond techniques can also be used to probe the carrier relaxation and transport in the presence of an applied electric field. We have already mentioned the experiment by Shank et al.[16] in which the velocity overshoot phenomenon in GaAs was investigated. In these experiments, Shank et al.[16] made use of the fact that the application of an electric field changes the absorption spectrum of GaAs because of the Franz-Keldysh effect.[36] When a low density of carriers is injected by a subpicosecond laser, the propagation of these carriers creates an opposing field and results in a change in absorption ($\Delta\alpha$) due to a reduction in the Franz-Keldysh effect. The transport dynamics are obtained by measuring the time evolution of $\Delta\alpha$ by the pump and probe technique and comparing it with a calculated curve using the electron velocity $v_e(t)$ as an adjustable parameter. Their results, shown in Fig. 10, imply large initial electron velocities followed by relaxation to velocities approximating the electron saturated velocity. These measurements provide the first evidence for the velocity overshoot phenomenon predicted by Maloney and Frey.[37]
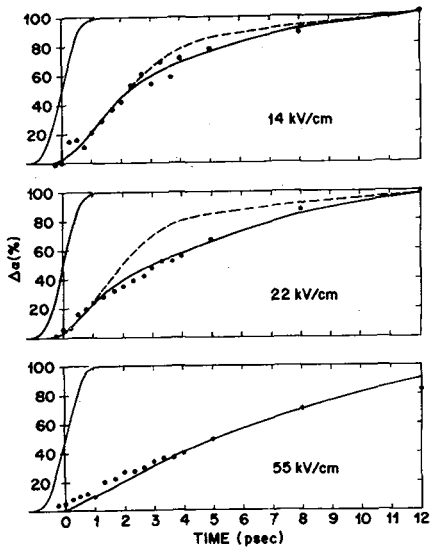
Fig. 10 Optical absorption change $\Delta\alpha$ vs. time delay at three applied electric fields. The individual points are experimental. For 14 kV/cm the solid line is a calculated curve using two constant velocity regimes; $v_e = 3.0 \times 10^7$ cm/sec (t<2.4 psec) and $v_e = 1.0 \times 10^7$ cm/sec (t>2.4 psec). For 22 kV/cm the solid curve is calculated with $v_e = 4.4 \times 10^7$ cm/sec (t<1.1 psec) and $v_e = 1.2 \times 10^7$ cm/sec (t>1.1 psec). The dashed curves show the continuation of $\Delta\alpha(t)$ if v_e remains constant. For 55 kV/cm the solid curve is calculated with $v_e - 1.3 \times 10^7$ cm/sec for all t. The curve at the far left of each trace shows the instrumental response (from Shank et al., Ref. 16).

We conclude our discussion of experimental results by discussing a recent experiment by Degani et al.,[38] in which the velocity field characteristics for photoexcited minority electrons in p- $In_{0.53}Ga_{0.47}As$, ($p_0 \approx 5 \times 10^{16}$ cm^{-3}) were measured. The experimental structure was 80 μm wide and had a 120 μm source-drain separation. The sample was mounted as a part of 50 ohm strip line circuit, and was weakly photoexcited by ~10 psec laser pulses a distance d from the drain. The photoresponse of the device was measured with a sampling scope and averaged with a multichannel analyser. For a given applied field, the drift velocity of photoexcited electrons was determined from the slope of the transit length (d) vs pulse widths of photo response. The drift velocities deduced in this manner are plotted in Fig. 11 as a function of applied electric field and compared with the calculation of Littlejohn et al.[39] for the majority carriers in the n-type $In_{0.53}Ga_{0.47}As$. We see that the drift velocity of photo-excited electrons continues to increase monotonically with applied field (i.e., exhibits no negative differential mobility) and reaches values as high as 2.6×10^7 cm/sec at 7.5 kV/cm. This is an interesting result from the point of view of making fast devices. Recent photoluminescence study of n- and p-type $In_{0.53}Ga_{0.47}As$ shows[40] that p-type samples show substantially smaller photoinduced heating of carriers than n-type and undoped samples. These luminescence results can be interpreted in terms of electron-hole interactions and strong hole-lattice coupling. The absence of negative differential mobility of photoexcited minority electrons in the high field measurements
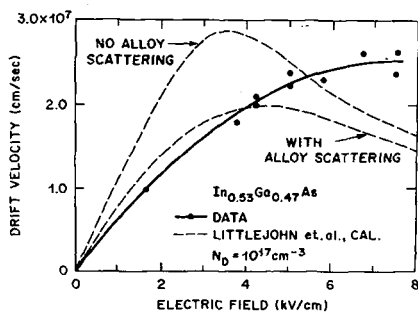
Fig. 11 Electron drift velocity as a function of applied electric field for p-type $In_{0.53}Ga_{0.47}As$. The bold line, drawn through the data points, can be compared to the velocity-field calculation of Littlejohn et al. (Ref. 39) for n-type $In_{0.53}Ga_{0.47}As$ with $N_D = 10^{17}cm^{-3}$. (From Degani et al. Ref. 38).

discussed above was also attributed[39] to reduced heating of electrons, and hence reduced probability of electron transfer to upper valleys, because of the presence of holes. The experiments by Shank et al.[16] and the one just discussed, illustrate the usefulness of combining transport measurements with picosecond optical techniques.

IV. Conclusions

Optical techniques are extremely useful in the investigation of hot carrier relaxation in semiconductors in two distinct ways. First, they provide a means of determining the carrier distribution function under various experimental conditions. Second, photoexcitation provides a means of heating the carriers and thus facilitates the investigation of many parameters involved in hot carrier relaxation. Availability of picosecond and subpicosecond pulses in recent years has added an exciting new dimension in the study of hot carrier relaxation in semiconductors by optical techniques. We have discussed some basic theoretical considerations essential in understanding such picosecond relaxation studies. It is clear that many challenging opportunities exist for theorists in this area. The calculation of the time evolution of the distribution function of photoexcited carriers on subpicosecond timescales is one example. We have reviewed some recent experimental work which illustrates how direct information about hot carrier relaxation can be obtained by using picosecond optical pulses. Experiments using pump-probe technique, luminescence technique as well as experiments combining transport and picosecond techniques have been performed. Very high density ($> 10^{20}$ cm^{-3}) plasma has been created and investigated using picosecond lasers. These experiments have enabled a direct measurement of carrier energy loss rates, demonstrated the importance of screening and provided evidence for the velocity overshoot phenomenon predicted previously. These experiments have also shown that photoexcited carriers reach a Maxwellian distribution function (with $T_c > T_L$) in less than 10 psec. The region below 10 psec (to $\approx$ 0.2 psec) is now accessible

and should yield more information about various relaxation processes. Application of picosecond pulses to investigate hot carrier relaxation promises to be an active and fruitful field of research in coming years.

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